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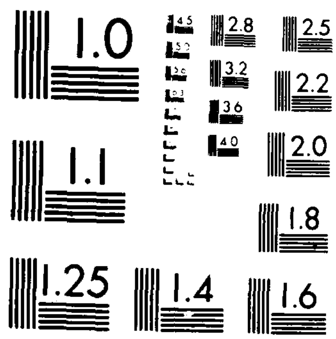
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AFGL-TR-87-0325

SURFACE DISTURBANCES PRODUCED BY LOW-LEVEL, SUBSONIC B-1 AIRCRAFT

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15 November 1987

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This technical report has been reviewed and is approved for publication.

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FOR THE COMMANDER

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Properties of infrasonic and seismic disturbances excited by low level, subsonic B-1 flights over the Arkansas River Valley near La Junta, Colorado are measured and studied for different wind conditions. The study emphasizes the role seismics and infrasonics might play to detect and track aircraft overflying a distributed network of pressure sensors and seismometers. The work concludes that carefully sited and calibrated seismic nodal elements, operating at low data rates, have a high potential to provide timely azimuth information for tracking.

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SURFACE DISTURBANCES PRODUCED BY LOW-LEVEL, B-1 SUBSONIC AIRCRAFT

I. Introduction

There is a growing requirement to explore new technologies to detect and track small cross section, low altitude, subsonic aircraft. To meet this need we measure and describe infrasonic and seismic disturbances generated by low altitude, subsonic B-1 flights over the Arkansas River Valley at the Hackamore Ranch, just east of La Junta, Colorado, Figure 1. The work is viewed as a preliminary step towards defining nodal elements of a system that automatically detects and tracks low altitude flights over a passive network of seismic and infrasonic sensors. The study also explores roles that seismic observations might play to extend tracking performance of distributed acoustic networks.

For the past decade, the Department of Defense has supported the advancement of distributed sensor network technology and its application to the detection and tracking of subsonic aircraft [1]. The early work focused on the pointing ability of small acoustic arrays in a wind noise environment. No comparable study has been undertaken to consider the performance of seismic network elements operating at substantially lower data rates that use very different pointing schemes. Abundant material is on hand to document the level of aircraft acoustics [2] and pressure effects produced by supersonic flights [3]. Also, it is well established that infrasonics generated by supersonic flights can produce intense seismics far from the flight path. Indeed, widespread "mystery booms" encountered after the introduction of transatlantic Concorde flights excited such a public outcry that a presidential inquiry was undertaken to explain them [4]. Flight operations were subsequently altered to muffle Concorde ground tremors in the Northeastern US. In contrast to supersonic operations, documentation treating infrasonics and seismics generated by subsonic flights is scattered and fragmentary. Seismic phase and amplitude data needed to differentiate between source azimuth and seismic wave direction are virtually nonexistent for atmospheric emitters.

Surface seismics generated by infrasonic loads are extremely sensitive to ground structure [5, 6, 7]. Further, it's well recognized that the ground responds quite differently to slowly moving wind generated pressure fluctuations and fluctuations of the same frequency and strength produced by an infrasonic load [8]. Ground admittance, the ratio of the ground motion to the applied load, can exceed 200 mm/sec/psi in ground structures that support "air-coupled" surface waves [9]. Conspicuous ground tremors (10 millimicrons/sec) can be excited by relatively weak infrasonic "signals" (25 db) buried in wind "noise". Furthermore, the ground particle motion excited by an infrasonic load contains azimuth information for network tracking without array processing [6].

The immediate aim of this study is to establish the signal and noise properties of infrasonic and seismic measurements generated by B-1 aircraft for one site over a range of wind conditions. Seismics produced by flights at other places can then be inferred by convolving the infrasonic signals obtained here with admittance operators proper to those sites [10]. The potential range and network density to detect aircraft can then be inferred from the relative strength of synthetic seismic signals against the local background noise. Signal-to-noise estimates such as these are basic to setting the spacing and information rate needed to detect and track aircraft. Tracking by low frequency, single point seismics can anticipate much lower data rates than small acoustic arrays. Unlike acoustics, seismic tracking will require a large initial calibration effort to cope with site specific admittances and pointing distortions caused by ground structure. A generic high performance seismic design is unlikely.

II. Findings

The intensity of a seismic disturbance generated by a B-1 flight over an open, smooth (reverberation free) area is determined by the site's normal acoustic admittance (a time invariant, linear operator) and an infrasonic pressure established by the flight and aircraft parameters. Spatially coherent infrasonic "signals" produced by flights are superimposed on an incoherent pressure field whose strength depends on wind speed [1,11].

The seismic background "noise" at the Hackamore Ranch site is largely insensitive to wind generated surface pressure. The overall "apparent" admittance at infrasonic frequencies, computed from the ratio of the total seismics to total pressure during periods free of infrasonic signals is something less than 1.0 mm/sec/psi. The same admittance computation for infrasonic loads is larger by about two orders of magnitude. Seismic reception at the Hackamore Ranch only weakly depends on wind level. Infrasonic or acoustic detection and tracking at this site at the same signal-to-noise level calls for processing a number of sensors to suppress in-band, wind generated pressure fluctuations.

Low altitude B-1 aircraft approaching the Hackamore Ranch at Mach 0.85

from the north produce broadband infrasonic signals with a spectral maximum at 3.0 Hz. Infrasonics impinging on the ground in turn excite narrowband ground disturbances that peak around 15 Hz. Seismics produced by low level flights passing east or west of the site are conspicuous events lasting for as much as a minute even under wind conditions that largely mask infrasonic disturbances. In one minute the B-1 travels about 20 km. A 15 km station spacing should permit tracking by two or more seismic nodes most of the time.

Admittance maxima excited by B-1 flights over the Hackamore Ranch range from 50 to 150 mm/sec/psi, depending on the propagation path defined by sensor and aircraft locations. Admittances found here are much more path sensitive than values at "well behaved", well sorted, flat layered sites that support boundary waves with a phase velocity around the speed of sound in air. The ability to demonstrate the use of seismics to detect and track aircraft by particle orbits, for example, can be considerably eased by seeking out wind resistant, low noise, uniformly responsive sites with a large admittance maximum below 10 Hz, either around La Junta or in an entirely new area. One such area is the Kennedy Space Center (KSC), Florida. Admittances there exceed 250 mm/sec/psi at 3.0 Hz [9]. Seismics excited by B-1 flights at KSC should be fifty times stronger (34 db) than seismics at the Hackamore Ranch, partly because of heightened ground sensitivity and partly because the frequency of the peak admittance at KSC better matches the peak B-1 pressure signal. Well behaved, low frequency, high admittance, wind resistant areas can also be found near Edwards AFB, California [6]. Playa sites at Edwards AFB are particularly interesting in the long run because they are regularly exposed to infrasonics from a large mix of well located, modern aircraft.

III. The Measurement System

The AFGL Geophysical Data Analysis System (GDAS) is a multi-channel, portable, digital system that acquires, stores, retrieves, analyzes and displays infrasonic and seismic measurements. As used here, GDAS sampled the output of a crossed linear array consisting of eight pairs of surface seismometer and "microphone" combinations as shown in Figure 2. Redundant measurements at the intersection of the two sensor lines are used to separate coherent signals from incoherent noise arising from turbulence and hardware sources. Simple summing of coherent signals embedded in a spatially incoherent "pressure noise" field enhances measurement quality by a factor directly proportional to the square root of the number of closely clustered measurement points [9].

GDAS measurement characteristics are determined with the sensors in place before and after the B-1 overflights. Figure 3 and Figure 4 depict nominal responses of the seismic and pressure channels. Hardware noise, obtained by cross-correlating nearly colocated seismometer outputs, is found to be a minor contributor. RMS noise for B-1 seismics around the peak ground response is estimated to be about 3% when computed from the square root of the ratio of coherent and incoherent spectra between "colocated" seismometers, see Figure 5.

Hardware gains for seismic channels are set by peak seismics expected from low level, subsonic, SAC training sorties that pass north to south over the Hackamore Ranch, a couple of kilometers east or west of the measurement site. In contrast, the modest gain of the pressure channels is governed by the need to contain large wind driven pressure excursions in the linear range of the GDAS amplifiers and filters. Lastly, the system bandpass was chosen to clearly bracket peak pressure and ground motion frequencies produced by B-1 overflights.

IV. Ground Response to Point Loads

The seismic response of the Hackamore site to a surface load was first sought by measuring wavelets produced by an impulsive, concentrated, normal, surface force (hammer blow). For flat, well sorted, alluvial areas whose structure depends exclusively on depth, such impacts richly excite low mode boundary waves with a vertical particle motion that depends solely on source-observer offset [13]. The typical seismic disturbance for alluvial sites is strongly dispersed, with low frequencies attenuated least and arriving first [14]. When seismic surface wave velocity equals that of the air term, ground response can be intense, well in excess of 200 mm/sec/psi.

Figure 6 is the observed vertical motion produced by a hammer blow for one offset distance at four cardinal headings from a common point at the Hackamore Ranch. Ground response to a surface impact is narrow banded and path sensitive, Figure 7. Also, seismic group delay is substantially larger than that of the air path. Wavelet nonuniformities shown here arise from the distribution in low velocity sediments lying immediately under the array. The site does not uniformly support boundary waves around the speed of sound in air. However, the long duration and narrow frequency content of the wavelets does show that the area strongly reverberates under the action of a surface load.

Response of this site to hammer blows and aircraft infrasonics is sensitive to seemingly "small" changes in observer location (5 meters) as well as source position. Looking ahead, the area's response to B-1 infrasonics is also featured by position sensitive reverberations that are a maximum in an area included by stations 4 and 7, see Table 4.

Frequency and spectral width of the maximum response at the array center obtained from impacts at the 4 cardinal headings is summarized in Table 1. The frequency of peak response, spectral width and magnitude are all azimuth sensitive. The site has some potential to be calibrated to generate azimuth estimates based on its relative spatial response. It is widely recognized that lateral inhomogeneities affect surface waves. Railroad Valley near Ely, Nevada, for example, has an azimuth dependant dispersion that should allow azimuth estimates to low altitude, subsonic aircraft based solely on the frequency of air-coupled waves [14].

Table 1. Hammer Wavelet Sensitivity with Source Azimuth

Azimuth	Peak response	Width (half power points)
North	19.5 Hz	5.0 Hz
South	26.0 Hz	5.5 Hz
East*	18.5 Hz	3.0 Hz
West	21.5 Hz	5.0 Hz

* multiple maxima

V. Surface Noise Measurements at the Hackamore Ranch

Earlier measurements of surface seismics and pressures at the Hackamore Ranch show the ambient background at a point can be represented by a weighted, zero mean, stationary Gaussian process. For times free of B-1 generated signals, the environment is well described statistically by spectra. Further, background measurements between seismics and pressure at a "common" point, and pressure measurements between closely spaced points are uncorrelated [12]. Vertical component long term spectral estimates in the band 1.0 to 20.0 Hz lie between 5.0 E-12 and 2.0 E-10 $(mm/sec)^2$/Hz with a minimum value located somewhat above 10.0 Hz. In turn, long term "signal free" pressure spectra taken by sensors buried just below the surface decrease as the square of the frequency with a value of 3.0 E-09 at 1.0 Hz to 3.0 E-11 $(psi)^2$/Hz at 10.0 Hz. This spectral shape is a common characteristic of wind excited pressure measurements; the roll-off extends uniformly over several decades of frequency [11].

Long-term average power in Table 2 is given by octaves for pressure and seismic measurements along with an "effective" admittance value that is the ratio of the total in-band seismics to pressure. For times free of infrasonic disturbances, overall "effective" admittances (ratio of the strength of the ground motion to surface load due soley to wind in the band from 1 to 20 Hz) are less than 1 mm/sec/psi. Like admittances based on above ground pressure measurements are somewhat smaller.

Table 2. Long Term One Octave Averages

	Band 1 2.5 to 5	Band 2 5.0 to 10	Band 3 10 to 20	Units Hz.
Seismic	3.6144 E-10	3.2102 E-10	9.7988 E-10	$(mm/sec)^2$
Pressure	1.7145 E-09	8.9359 E-10	4.0462 E-10	$(psi)^2$
Admittance	0.459	0.599	1.556	mm/sec/psi

VI. B-1 Generated Pressures and Seismics

Flights by the same type aircraft operating under the same flight rules are expected to generate the same surface pressure "footprint" when overflying open, smooth topography. In contrast, seismics are controlled by the local ground structure as well as the flight "footprint".

Figures 8 through 11 are spectral estimates obtained from periodogram averaged data segments just before, during and following four B-1 overflights. For times before an obvious B-1 pressure signal, seismics between 10 to 20 Hz are significantly stronger than the long-term seismic background noise value. Samples taken shortly before and after flights produce readily identified narrowband seismics driven by inconspicuous infrasonics. The analysis given here focuses on four overflights, see Appendix A. The overflights were selected from a set of 24 to show wind effects on measurements for sorties passing east and west of the measurement site.

Figures 12a through 12f give coherence estimates between "colocated" pressure and seismic measurements for calm and windy conditions shortly before, during and after B-1 overflights. It is readily seen that infrasonics are highly correlated with seismic measurements; wind generated pressures are not.

Looking ahead to detection, high correlation between pressure and seismic measurements is a reliable indicator of infrasonic "signals". The linear relation between infrasonics and seismics [15] also allows a separation between wind induced pressure fluctuations and aircraft generated infrasonics. Figure 8b and Figure 8c are the total pressure spectra before and during a calm wind condition for a B-1 passing east of the measurement site. Total pressure spectra for the period of closest passage is further separated into an incoherent wind pressure and a coherent infrasonic spectral term through its correlation with seismic measurements. The incoherent residual, Figure 13, corresponds quite well in shape and level to the "wind" spectra just prior to the B-1's arrival. In turn, the coherent term in Figure 14 isolates B-1 infrasonics with a peak value of 4.0 E-09 $(\text{psi})^2$/Hz (86 db) at 3.0 Hz. The signal drops to 74 db at the beginning of the audible range (20 Hz). Separation between wind noise and B-1 infrasonics is nearly complete because seismics at the time of nearest passage are as much as 4 orders of magnitude greater than the seismic "noise" term in the 1 to 30 Hz band. Correlation between infrasonic pressure and seismics can be extended to avoid detection errors (false dismissal in the case of a high wind threshold and false alarm because of a purely seismic event).

Table 3 summarizes estimates of total pressure, incoherent "wind" pressure, coherent "infrasonic" pressure and seismics for an octave band around the peak ground response shortly before and during east track flyovers for calm and windy conditions. The relative strength of B-1 seismic and pressure "signals" measured by the jump in spectra before and during flyovers is noteworthy. The high signal-to-noise gain produced by the ground acting as a spatial velocity filter invariably penalizes bandwidth [6].

Table 3. Properties of the 10 to 20 Hz Passband			
Measurement	Windy	Calm	Units
Seismic			
Before	8.309 E-09	1.694 E-08	$(mm/sec)^2$
During	7.376 E-06	1.146 E-05	$(mm/sec)^2$
Seismic Power Ratio	887.7	676.5	(during/before)
Pressure			$(psi)^2$
Infrasonic			
Before	.158 E-09	.040 E-09	"
During	3.496 "	3.379 "	"
Wind			
Before	1.015 "	.199 "	"
During	1.031 "	.422 "	"
Total			
Before	1.173 "	.239 "	"
During	4.527 "	3.801 "	"
Pressure Power Ratio	3.86	15.88	(during/before)
Admittance Overall			
Effective	40.36	54.91	mm/sec/psi
Infrasonic	45.93	58.23	mm/sec/psi

VII. Spatial Relations

Seismics excited during a B-1 flight are highly coherent between station pairs for frequencies less than the maximum ground response, Figure 15. An abrupt coherency loss appears just above the peak response even in the short-term with the aircraft at nearly the same azimuth. For times free of B-1 disturbances, or around the time of closest passage, seismics between station pairs become uncorrelated over time in the fashion of a seismic field produced by sources over a range of directions, ie, with a gradual coherency loss with increasing frequency that is directly proportional to observer separation.

Pressure noise spectra obtained from periodograms averaged over time or spatially are equivalent. Wind generated surface spectra exhibit the classic inverse relation with frequency and overall level proportional to wind speed. Infrasonic signal strength is uniform over the Hackamore array. Coherence between pressures measured by surface sensors placed less than a meter apart is small for wind and high for infrasonics, Figure 16.

B-1 generated pressures propagate across the array coherently with an amplitude and phase in harmony with a pressure wave from a small, distant, moving source impinging on a smooth surface. In turn, ground motion has only a well structured, repeatable, position dependent pattern for frequencies less than, or equal to the main response. Seismic phasing between points above the "fundamental" response is erratic, even for short intervals with the B-1 at essentially the same azimuth.

Ground Response at the Hackamore Site

Ground admittance, computed from the square root of the ratio of the total seismic spectra to that portion of the pressure spectra that is coherent with the seismics, is given in Figure 17 for the array center. Admittance is sensitive to small changes in observer location. Table 4 is a compilation of admittance estimates for seven locations around the time of peak loading for a B-1 passing east of the array. Infrasonics dominate the Table 4 pressure measurements above 2.0 Hz. Admittances at positions 4 and 7 are significantly larger than values found elsewhere. The array center has a value midway between the extremes. The position sensitive characteristic of admittances seen in Table 4 is quite repeatable for all the east track sorties.

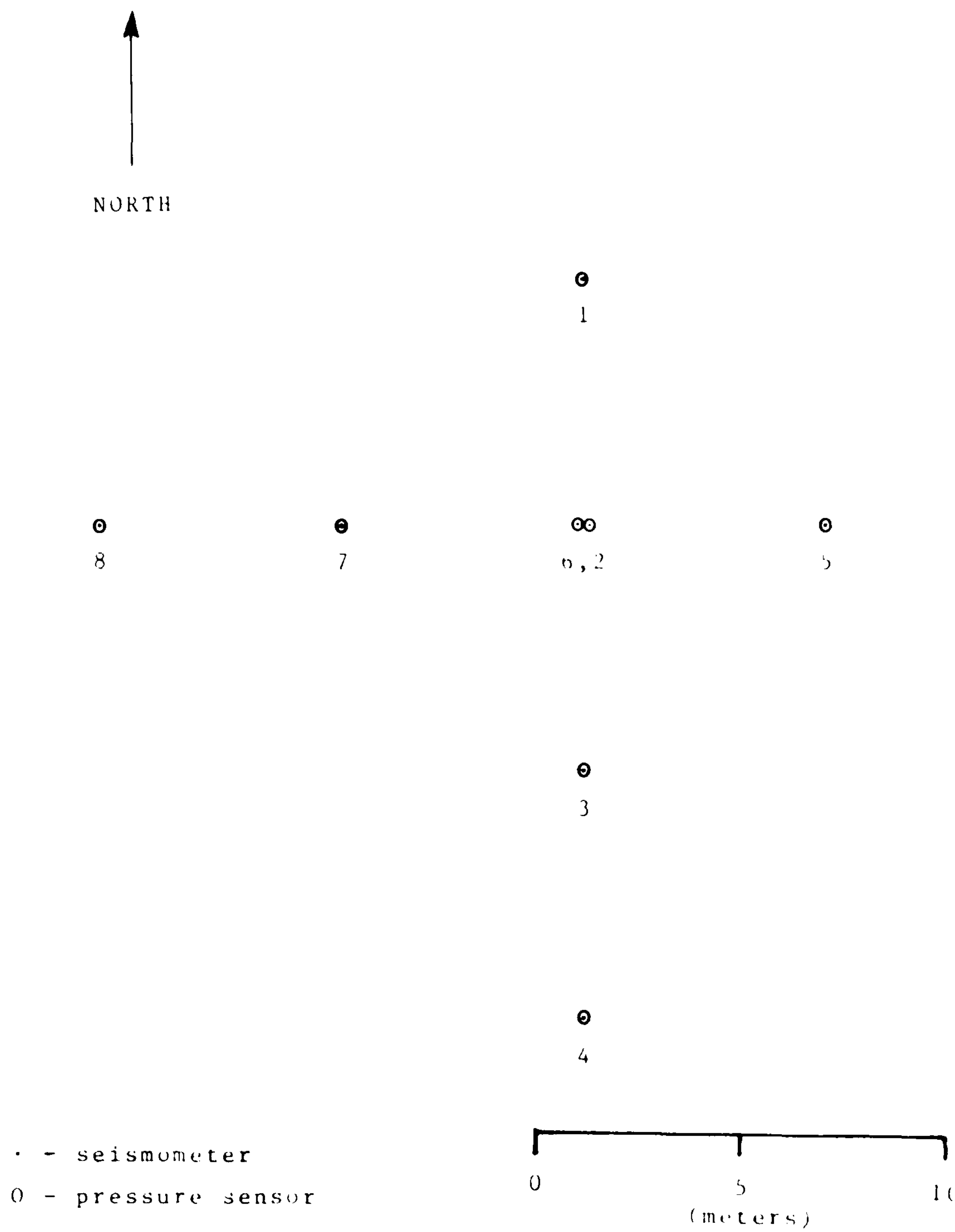
Sorties passing to the west produce a somewhat different pattern with a slightly larger admittance at the center.

Table 4. Admittance Maxima and Center Frequency

Position	Admittance	Center Frequency	
1	56.062 mm/sec/psi	19.0 Hz	
2	91.038 "	15.0 "	(center)
3	88.192 "	14.0 "	
4	141.421 "	13.0 "	
5	62.377 "	23.0 "	
6	91.038 "	15.0 "	(center)
7	141.421 "	13.0 "	
8	58.326 "	13.0 "	

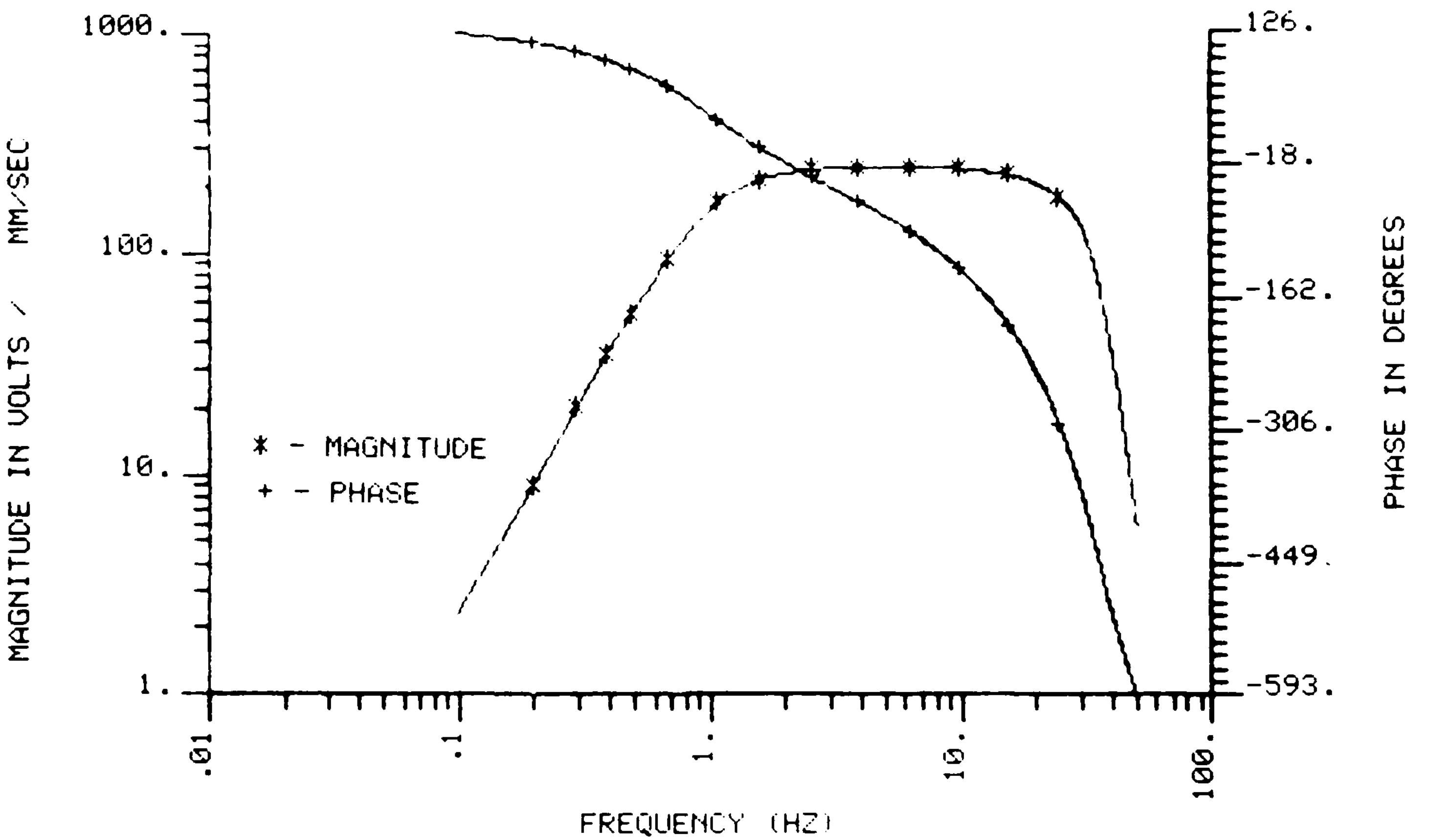
B-1 FLIGHT TRACK STATION, LA JUNTA, COLORADO

FIGURE 1



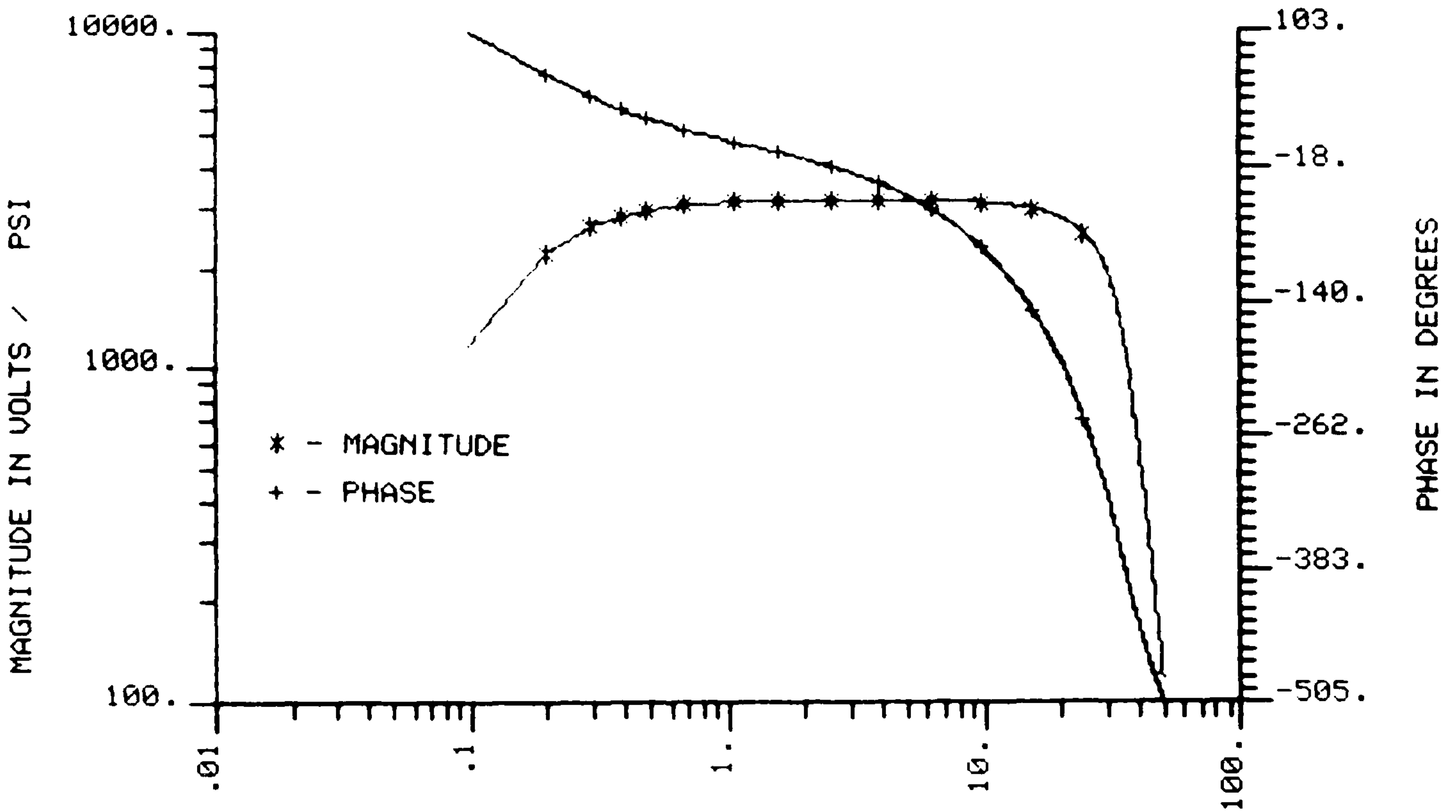
AFGL SEISMO-INFRASONIC ARRAY

FIGURE 2



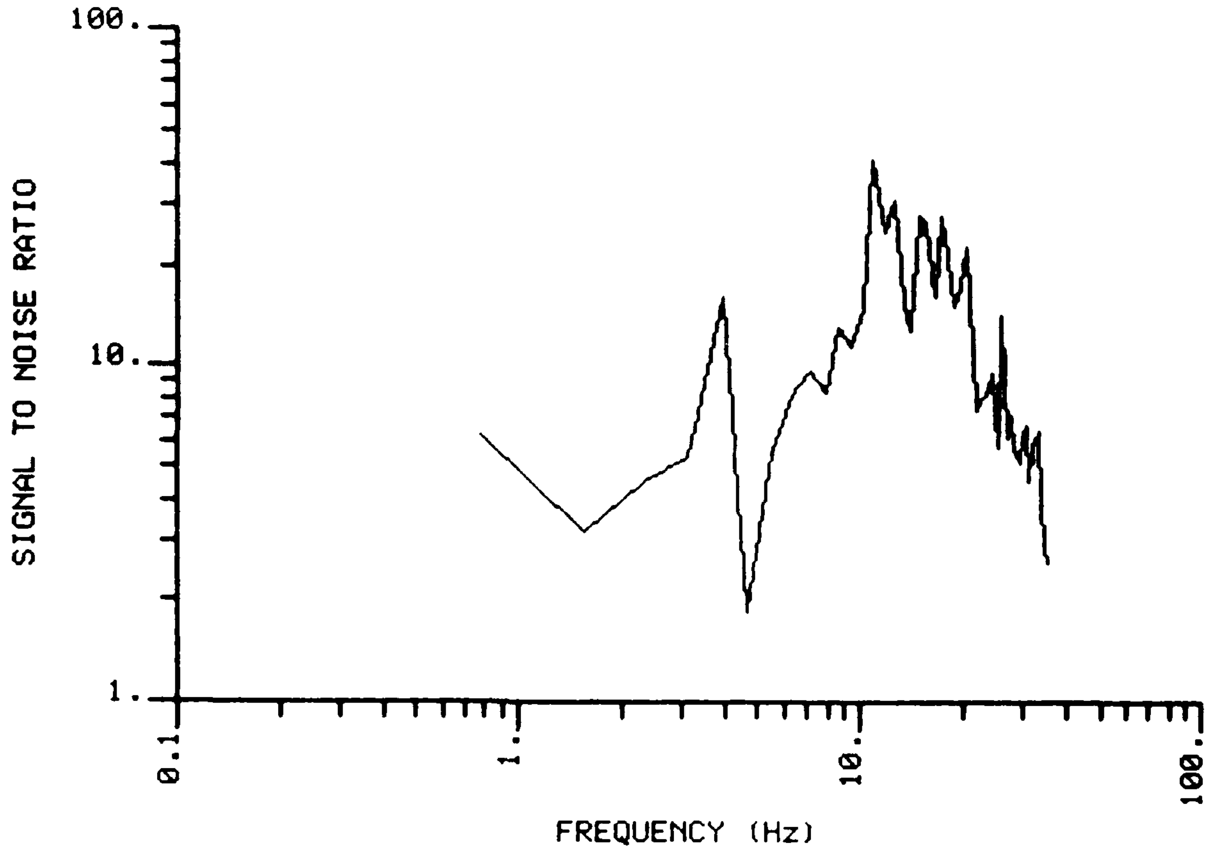
SEISMIC RESPONSE

FIGURE 3



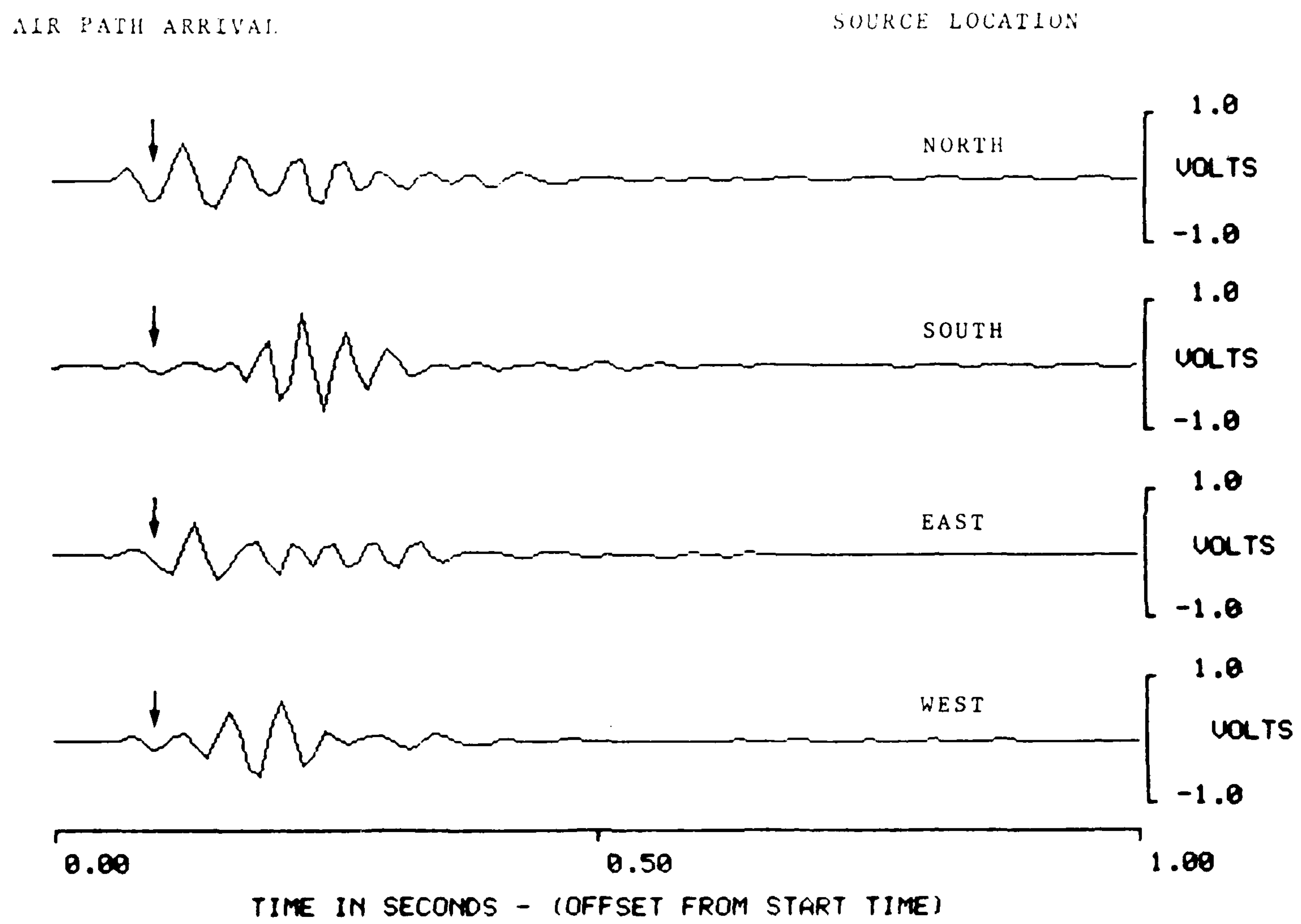
PRESSURE RESPONSE

FIGURE 4



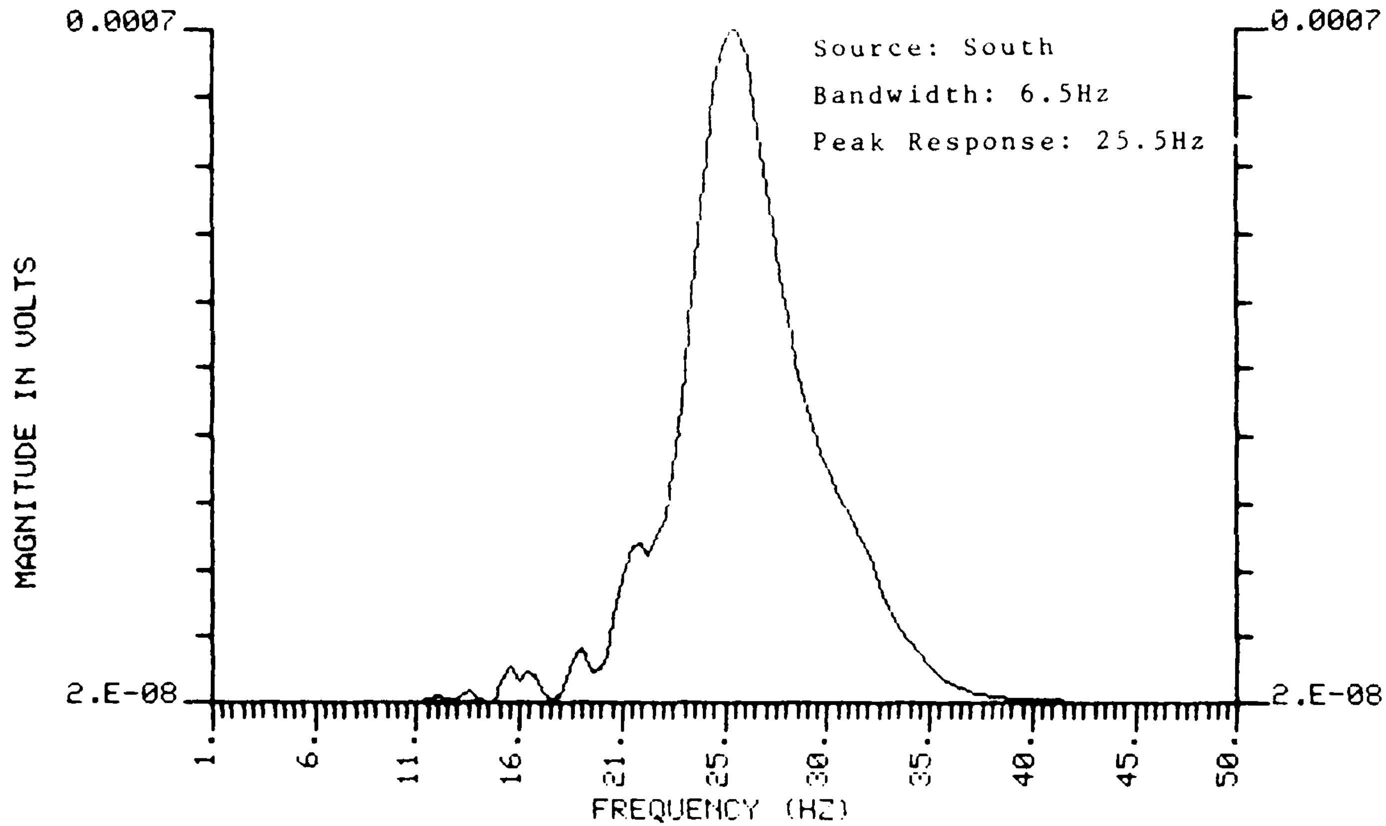
SEISMIC SIGNAL-TO-NOISE

FIGURE 5



HAMMER BLOW WAVELETS WITH AZIMUTH

FIGURE 6



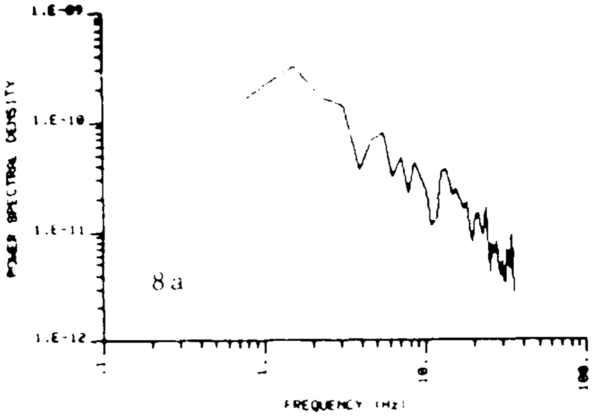
HAMMER BLOW WAVELETS AMPLITUDE SPECTRUM

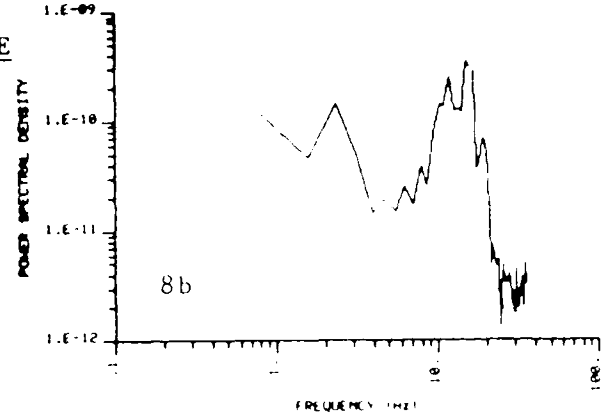
FIGURE 7

EAST TRACK/CALM RUN 26

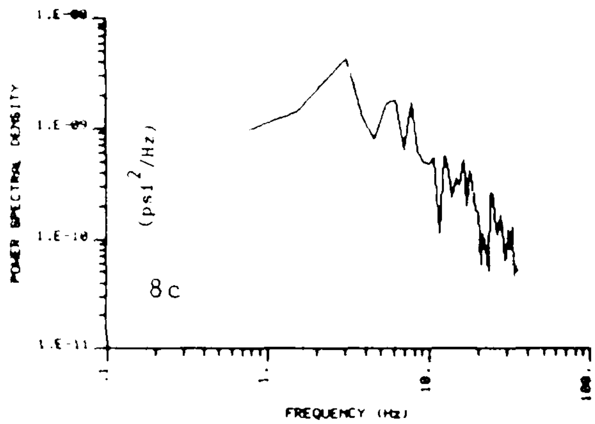
PRESSURE SEISMIC

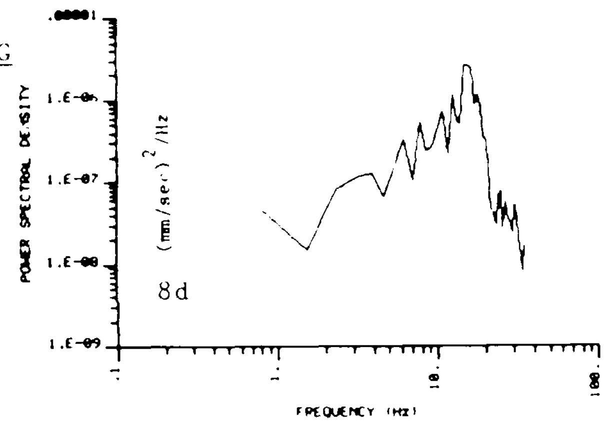
BEFORE





DURING





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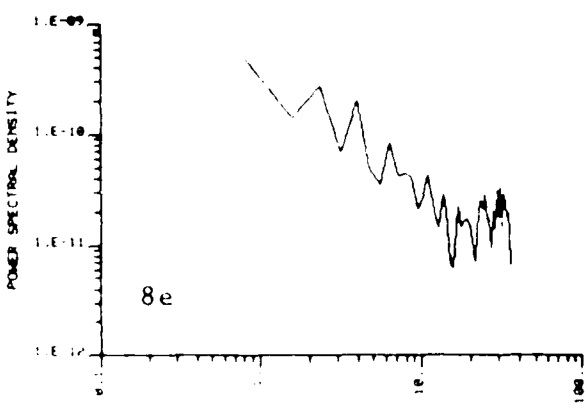
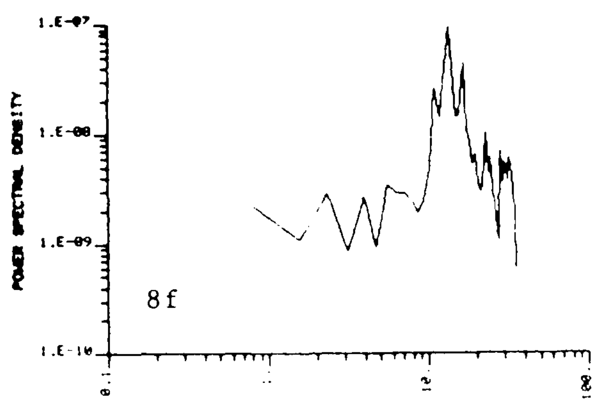


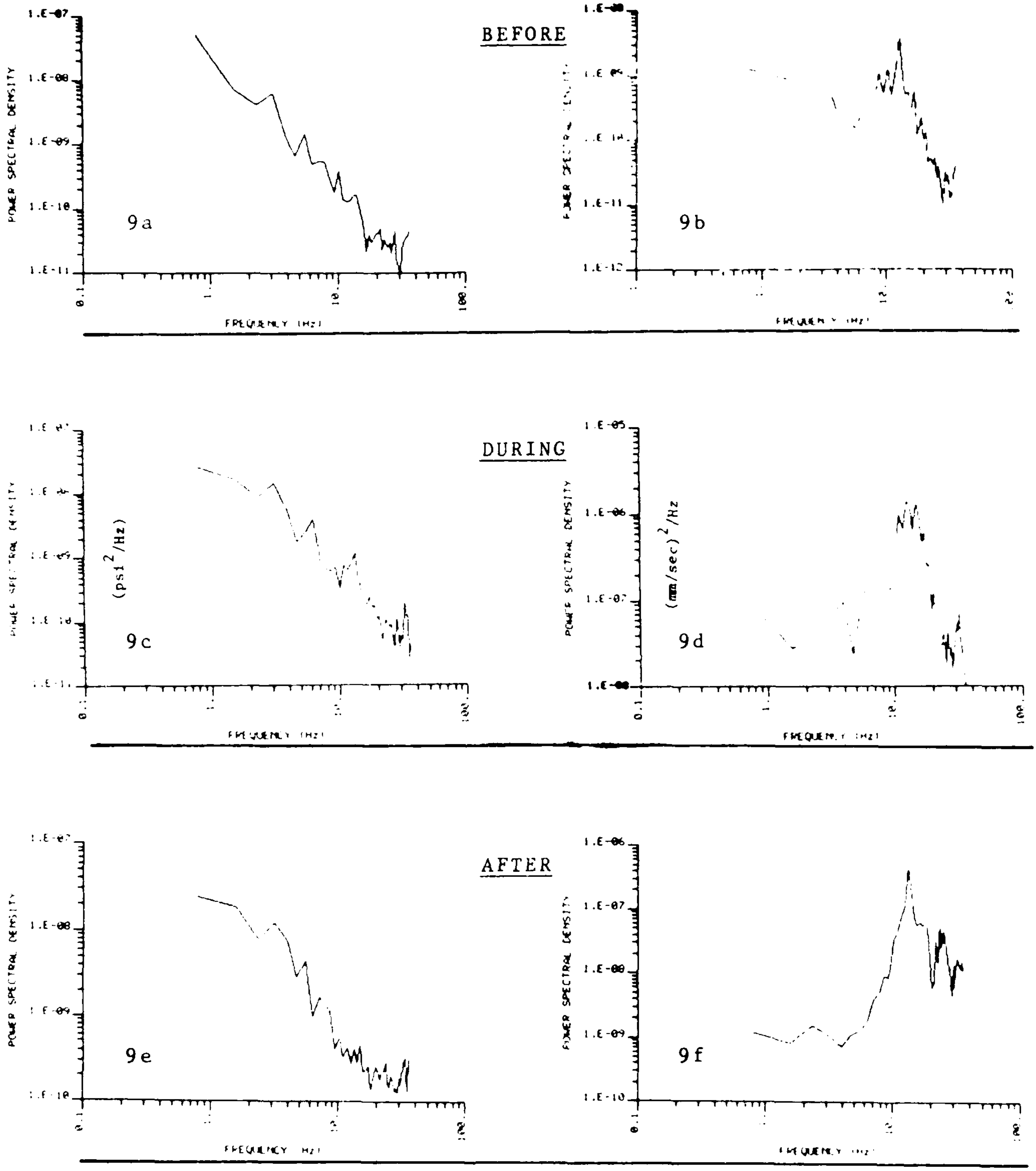


SPECTRAL ESTIMATES BEFORE, DURING AND AFTER FLYOVER

FIGURES 8a-8f

EAST TRACK/WINDY RUN 11

PRESSURE SEISMIC

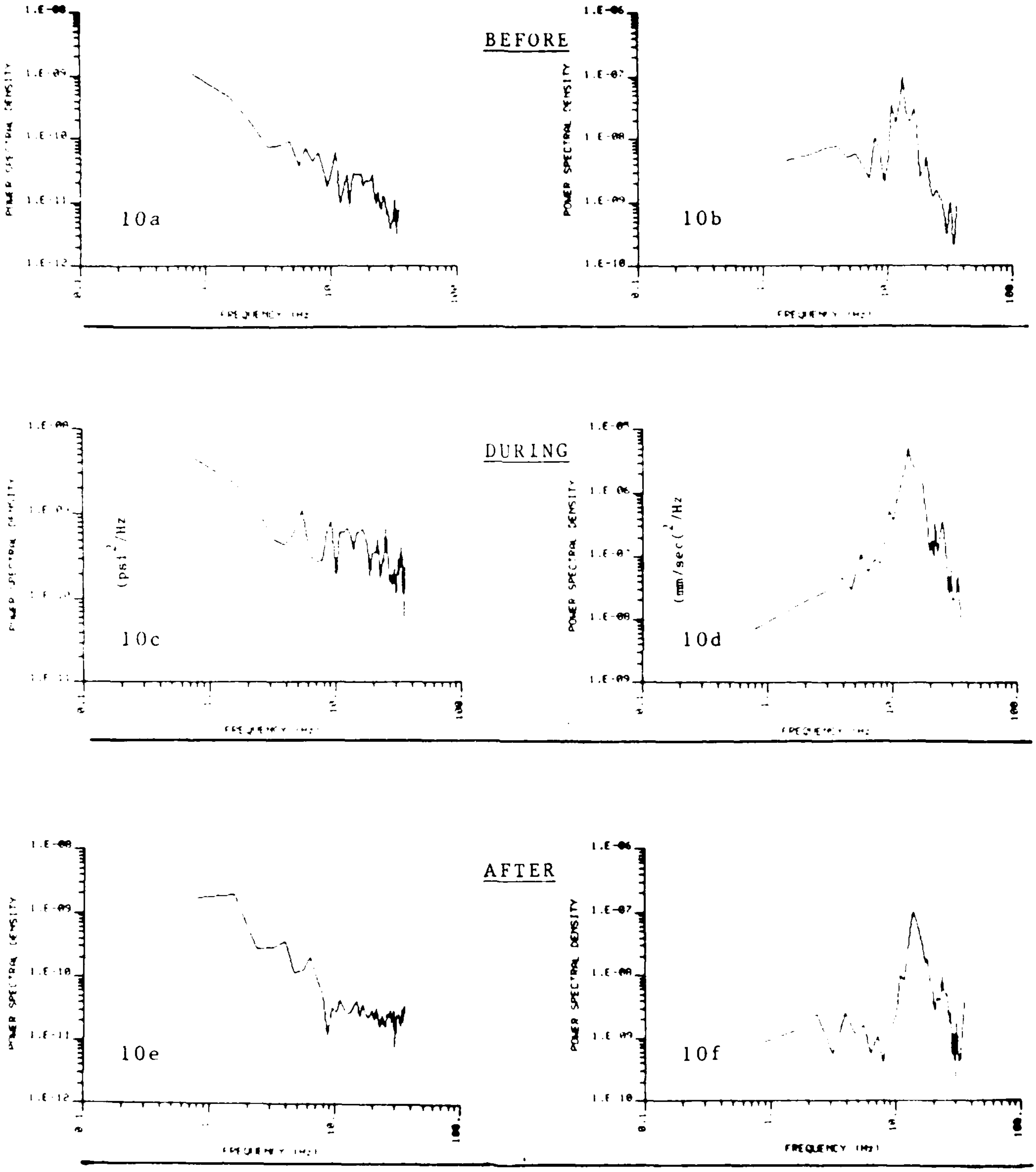


SPECTRAL ESTIMATES BEFORE, DURING AND AFTER FLYOVER

FIGURES 9a-9f

WEST TRACK/CALM RUN 08

PRESSURE SEISMIC

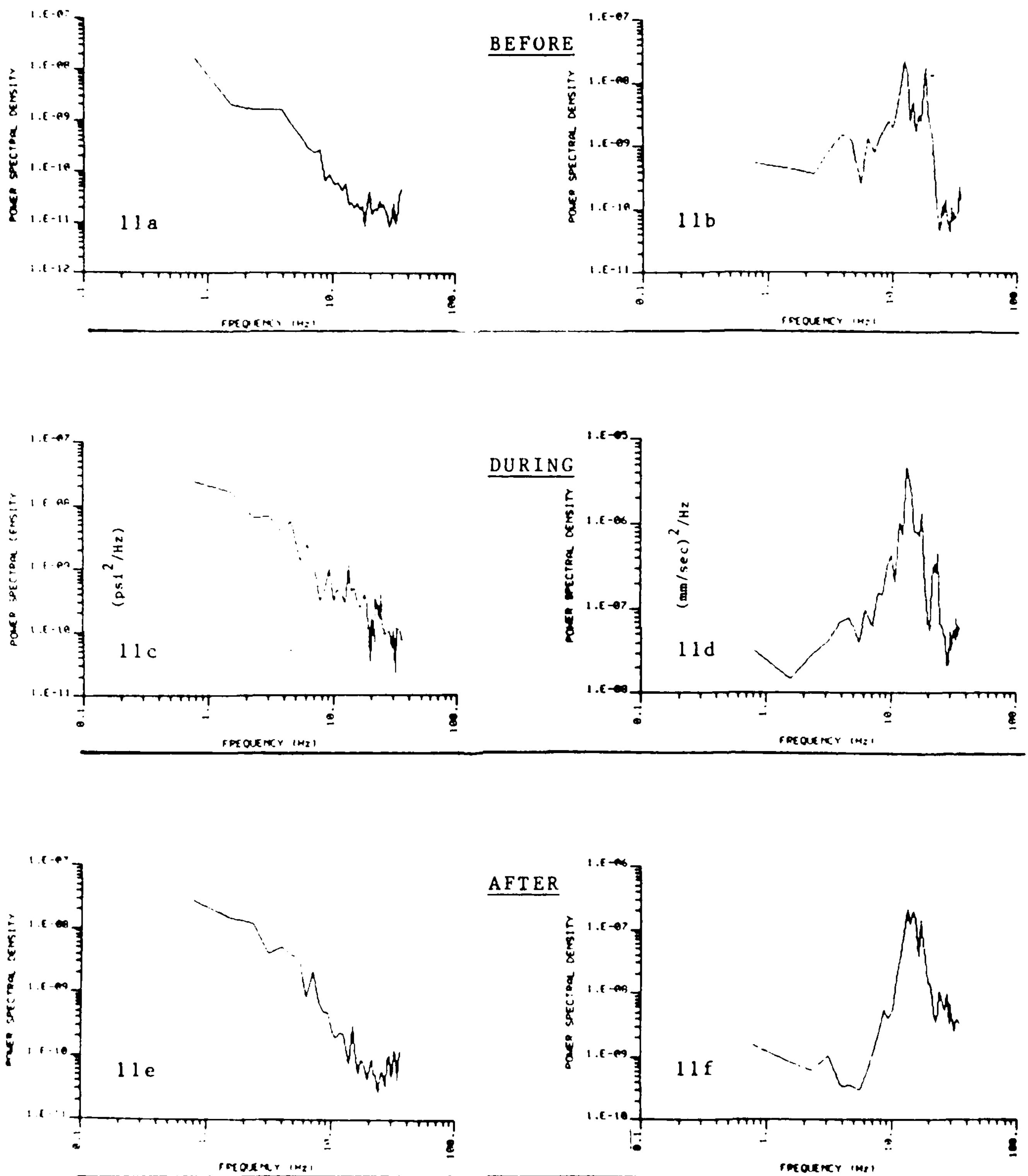


SPECTRAL ESTIMATES BEFORE, DURING AND AFTER FLYOVER

FIGURES 10a-10f

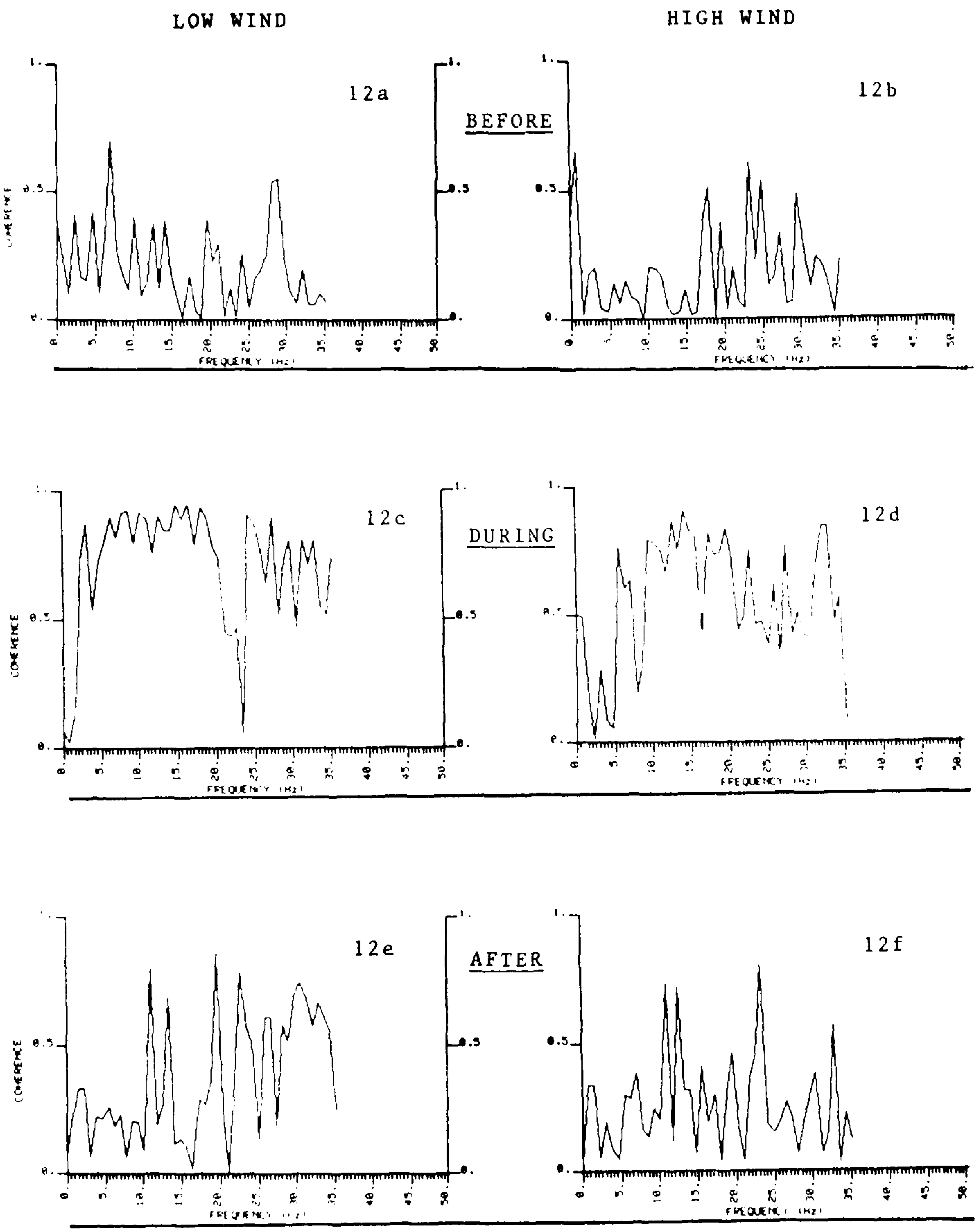
WEST TRACK/WINDY RUN 13

PRESSURE SEISMIC



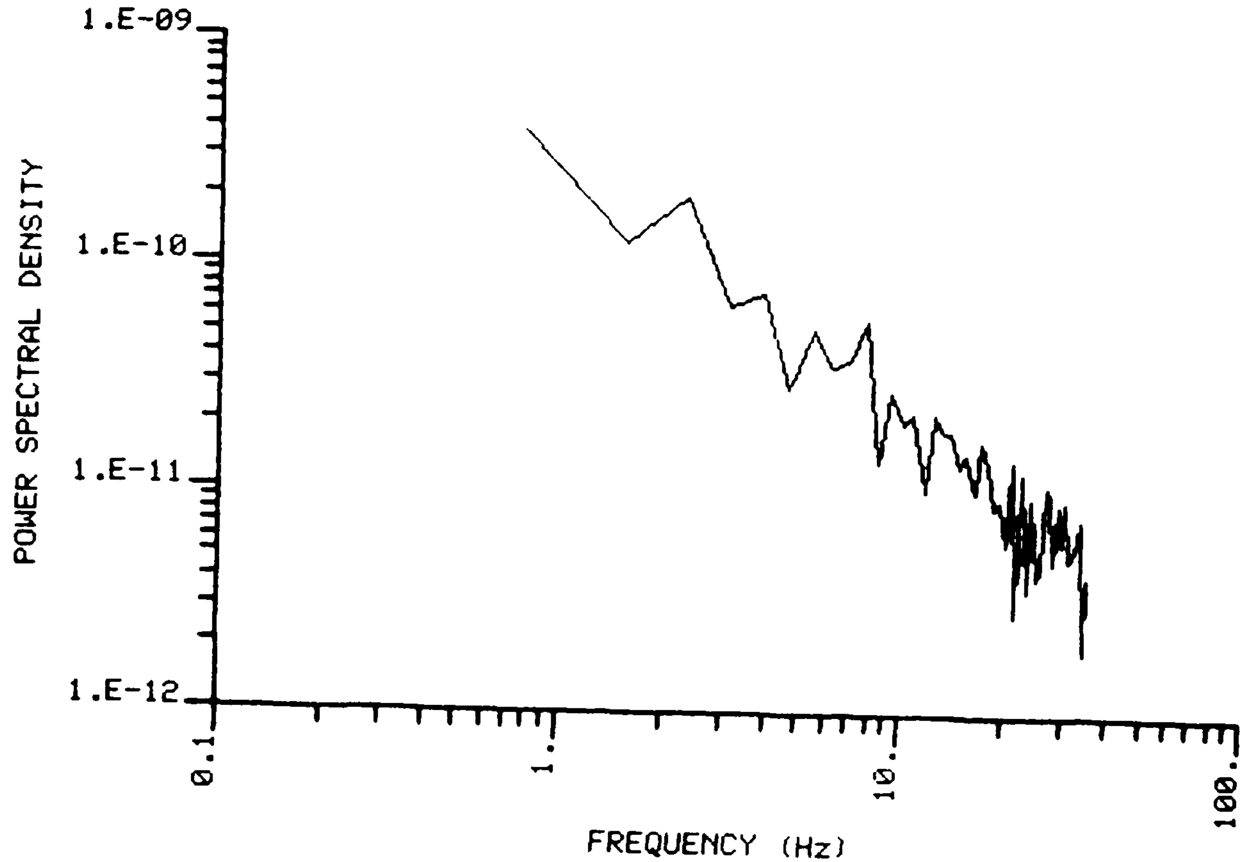
SPECTRAL ESTIMATES BEFORE, DURING AND AFTER FLYOVER

FIGURES 11a-11f



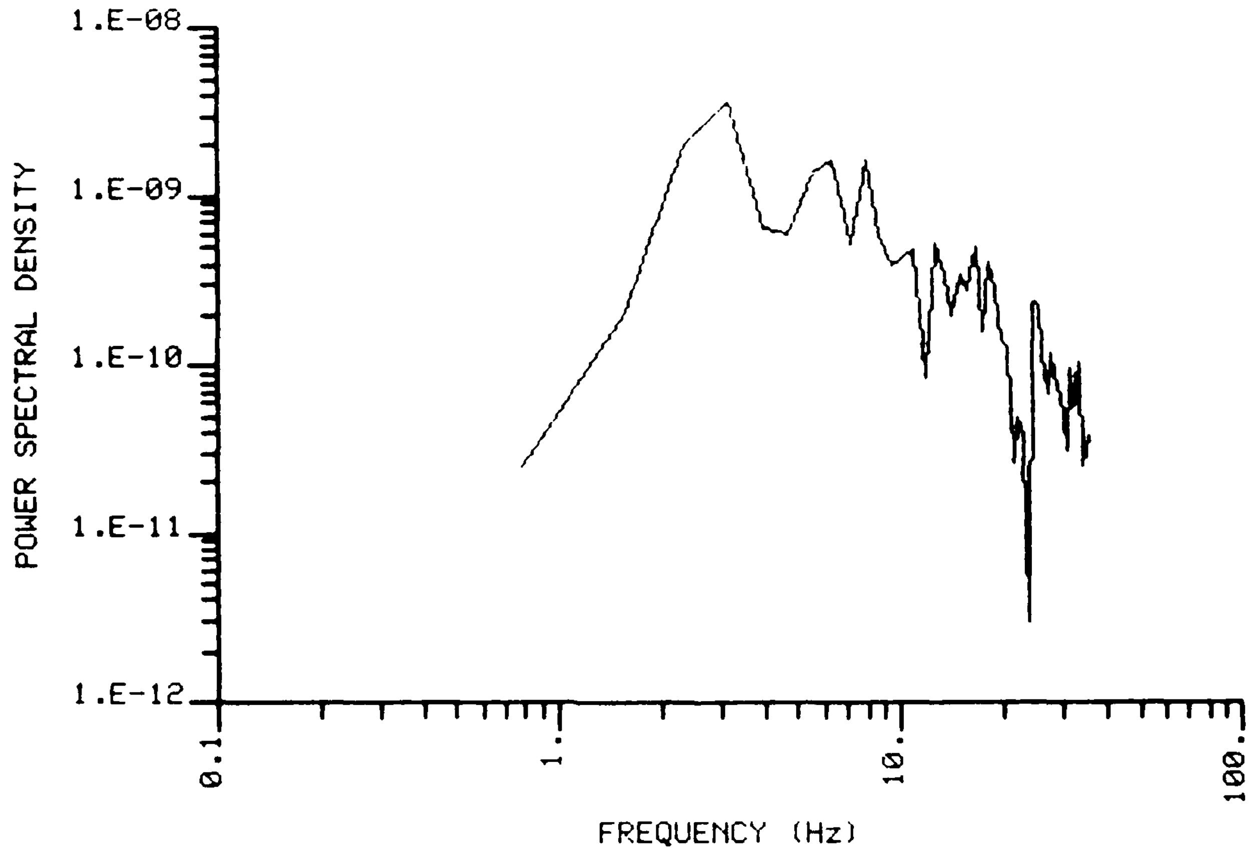
COHERENCE BETWEEN SEISMIC AND PRESSURE MEASUREMENTS FOR B-1 FLYOVER DURING HIGH AND LOW WIND CONDITIONS

FIGURES 12a-12f



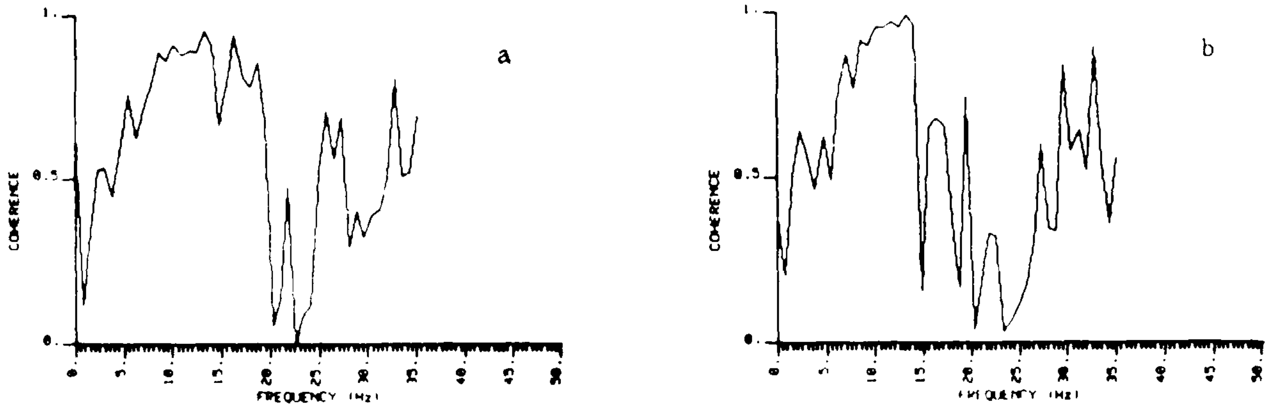
INCOHERENT WIND SPECTRA DURING FLIGHT 26

FIGURE 13

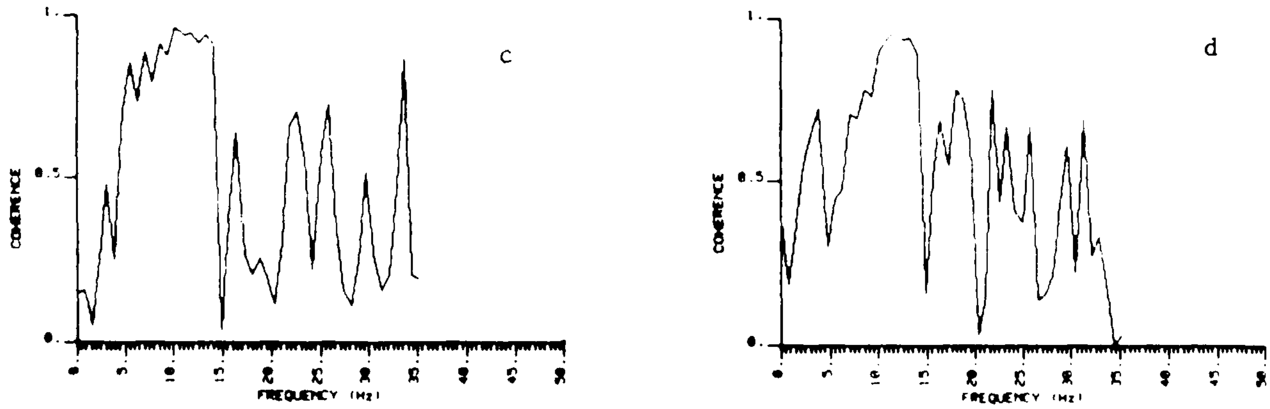


COHERENT B-1 INFRASONICS DURING FLIGHT 26

FIGURE 14



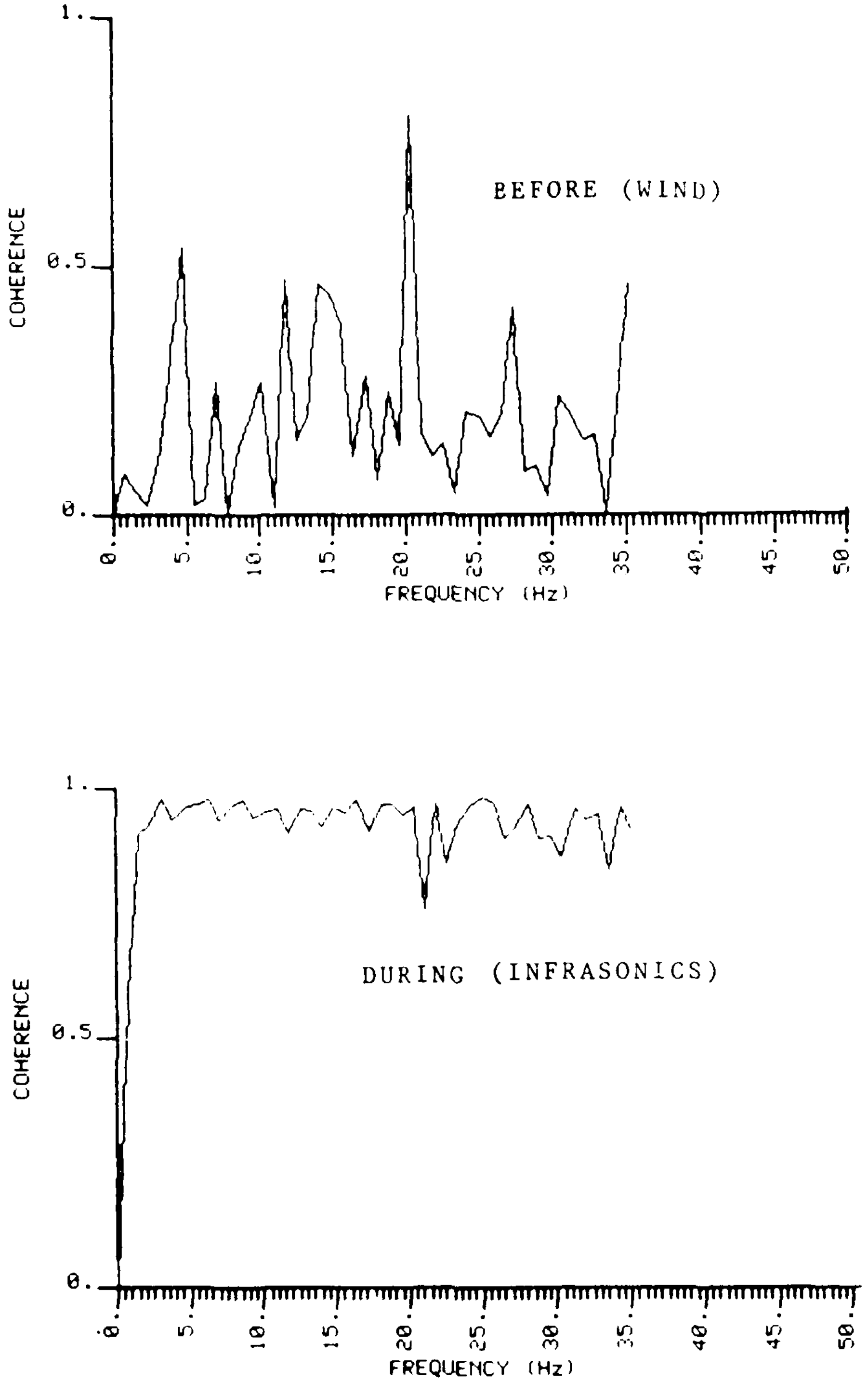
SEPARATION 20 FEET



SEPARATION 40 FEET

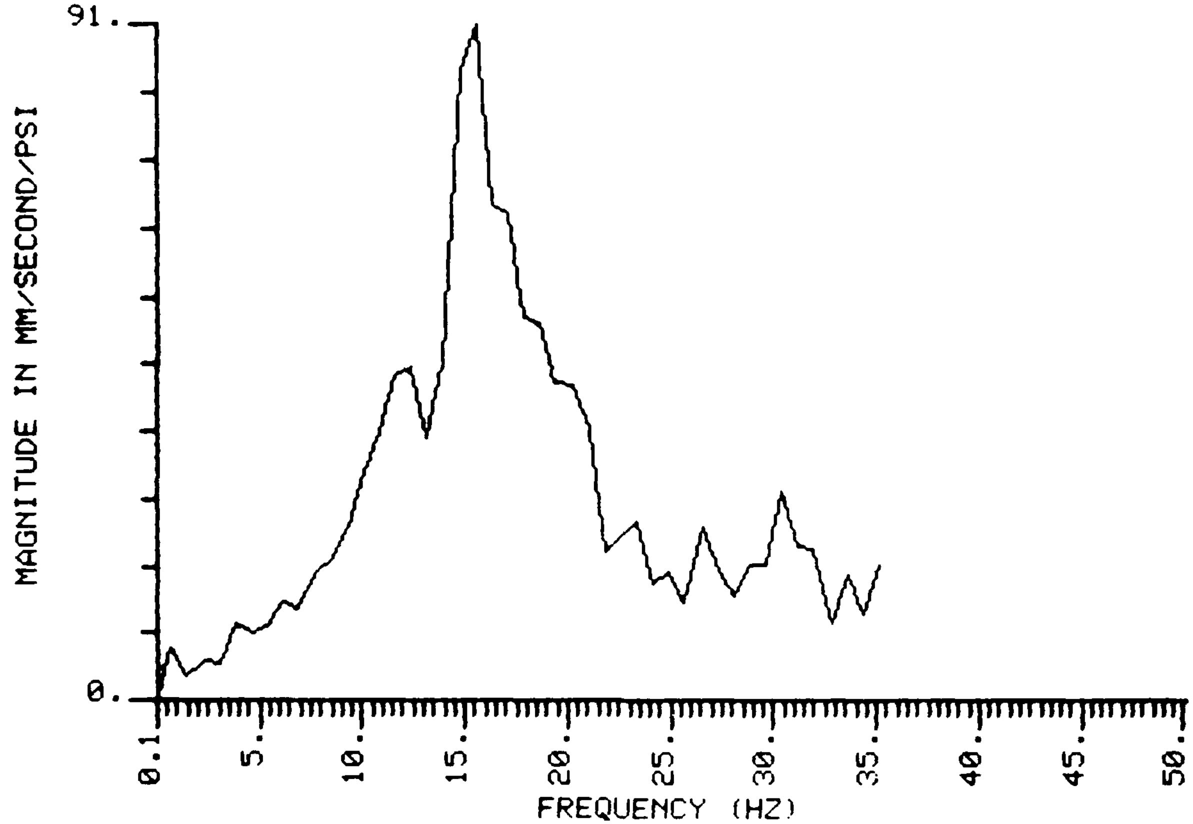
COHERENCY OF B-1 SEISMICS

FIGURE 15



COHERENCE FOR WIND PRESSURE AND B-1 INFRASONICS

FIGURE 16



SURFACE ADMITTANCE

FIGURE 17

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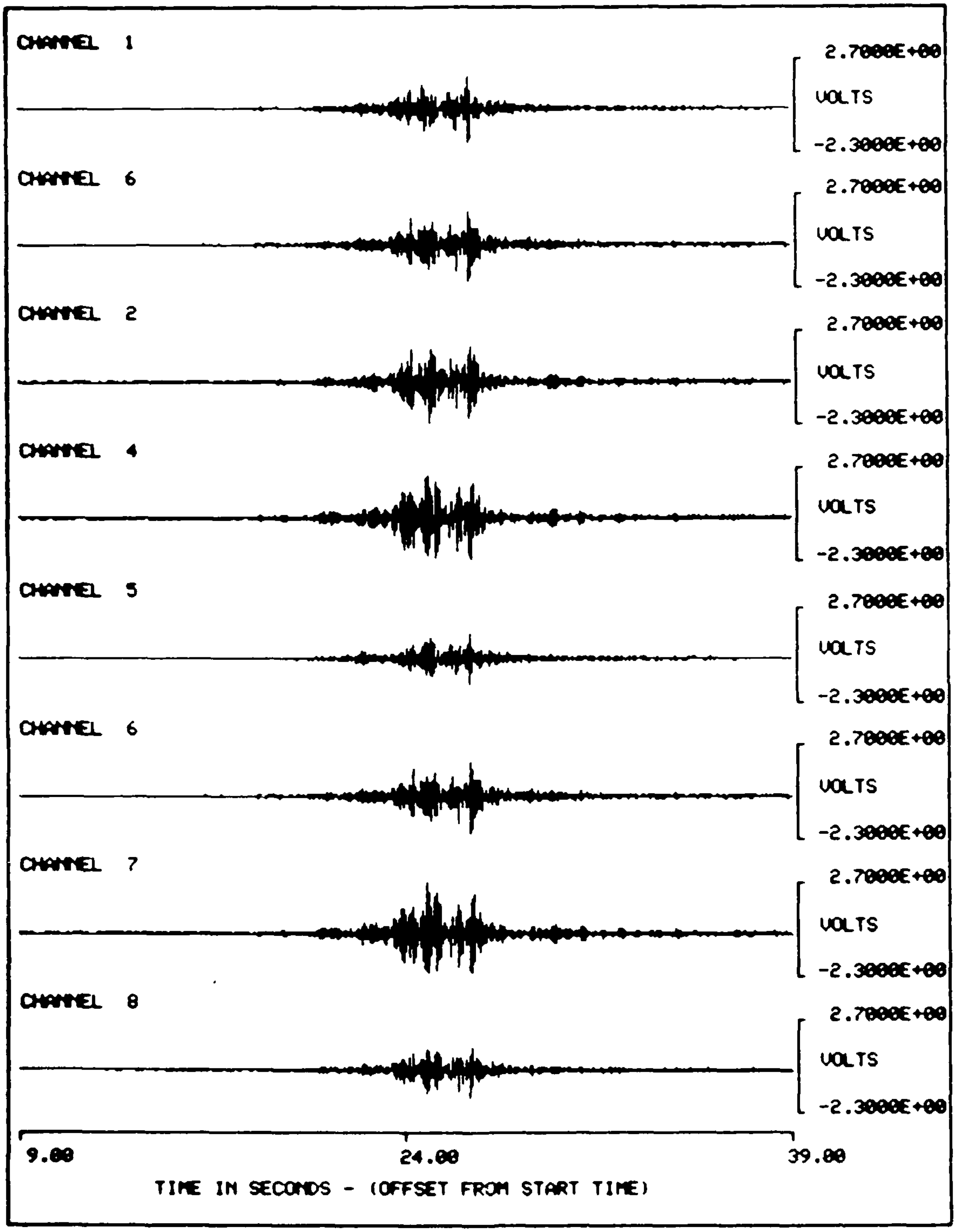
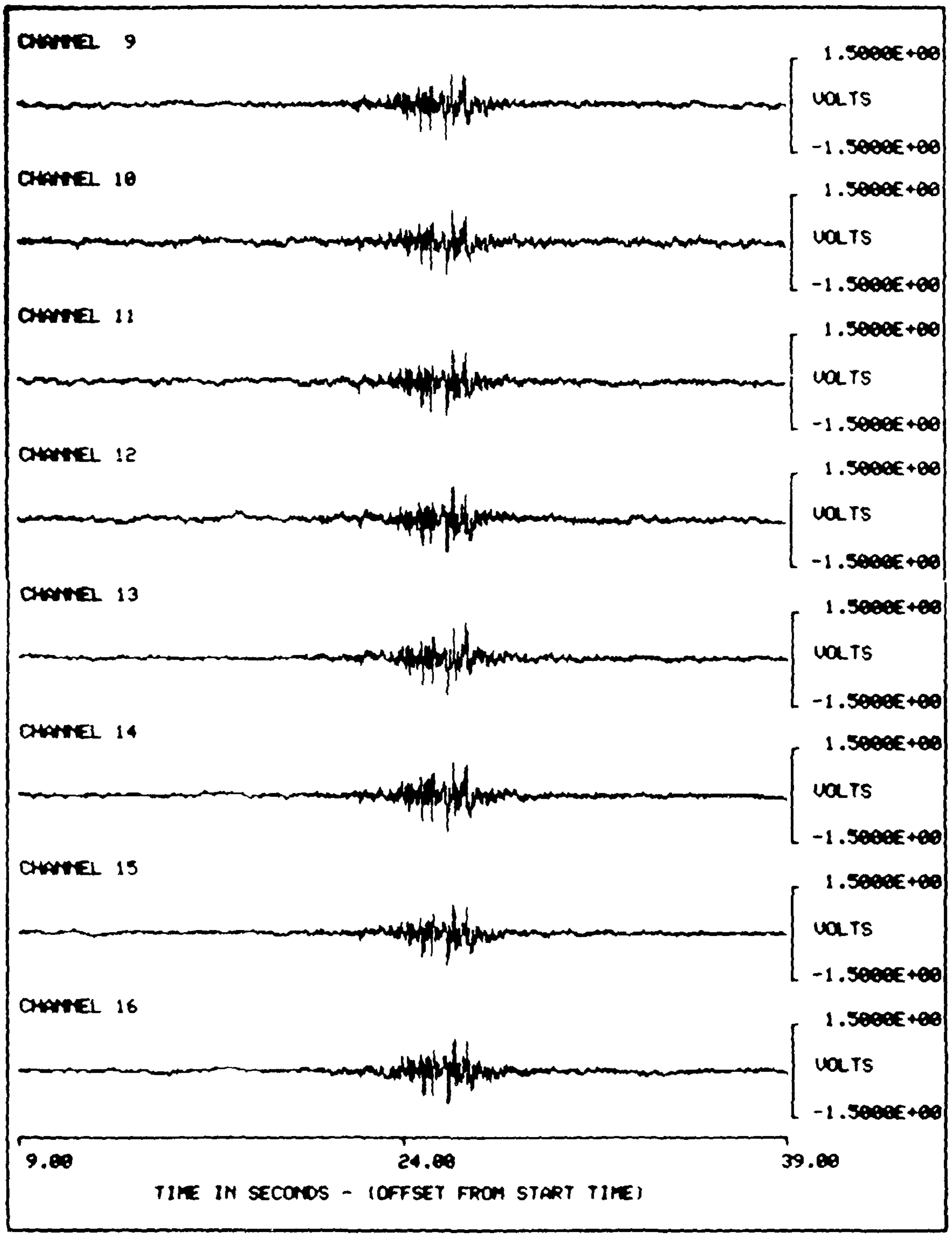
WIND AFFECTS ON MEASUREMENTS FOR SORTIES PASSING
EAST AND WEST OF THE MEASUREMENT SITE

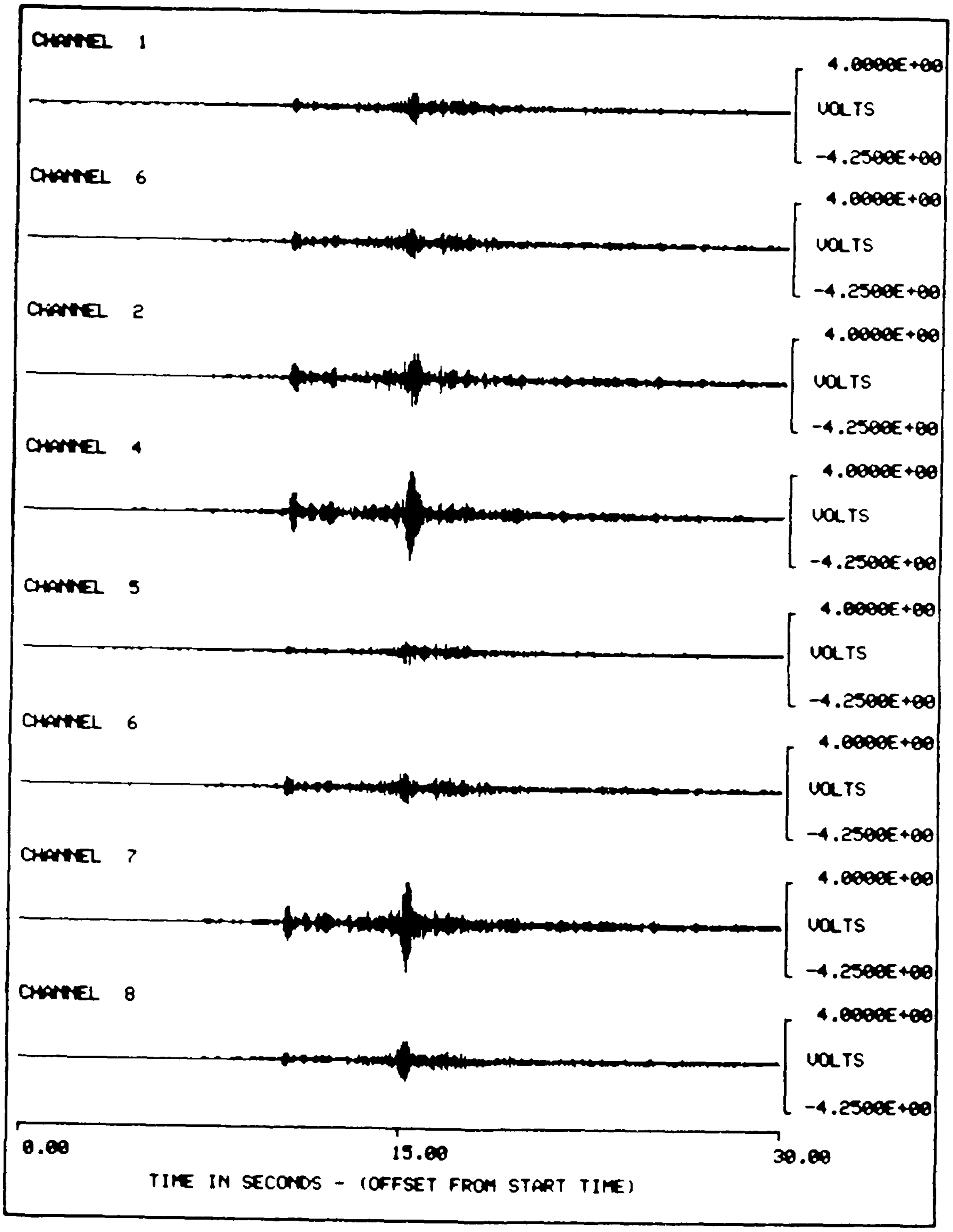
APPENDIX



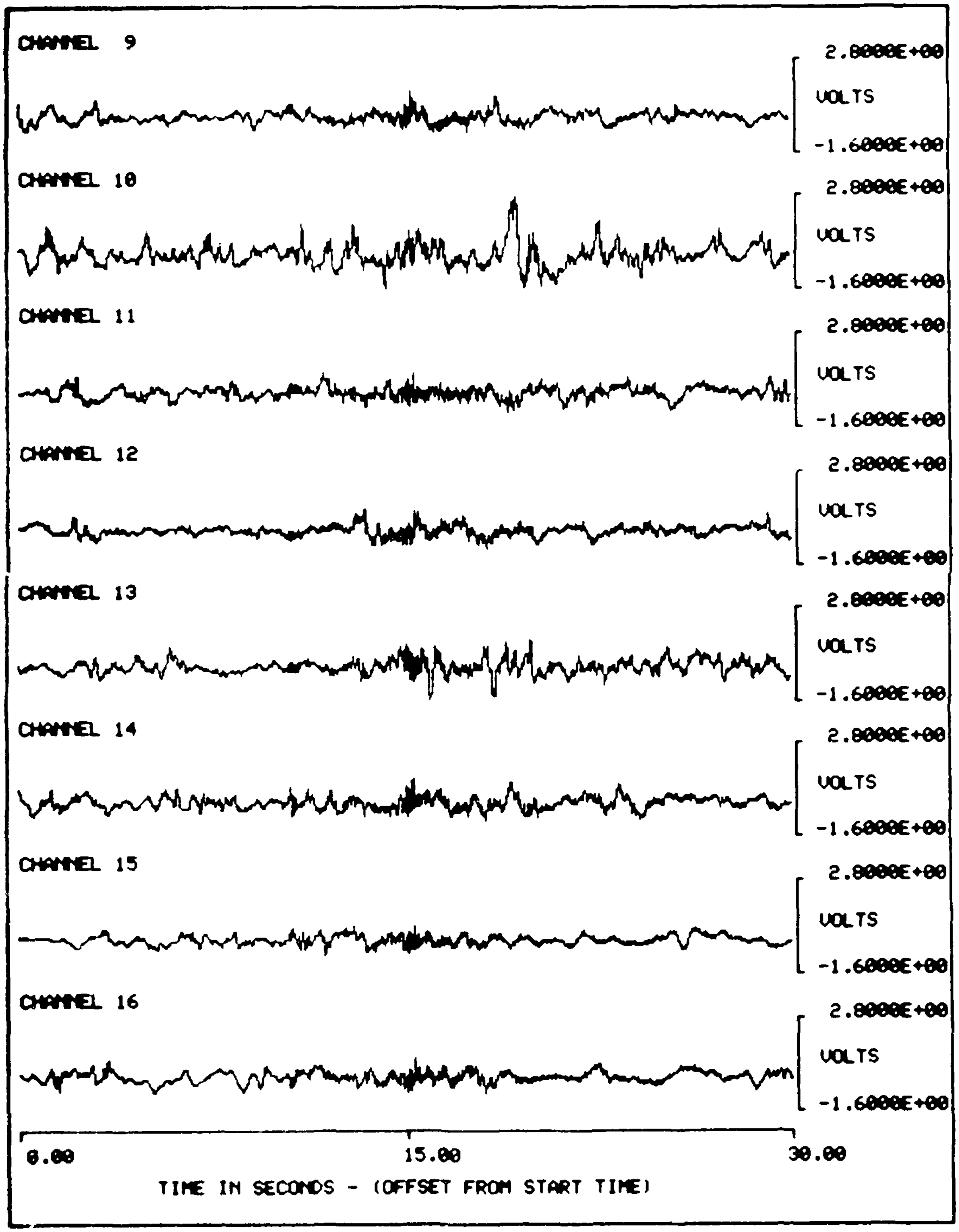
SEISMIC-EAST TRACK/CALM (RUN 26)



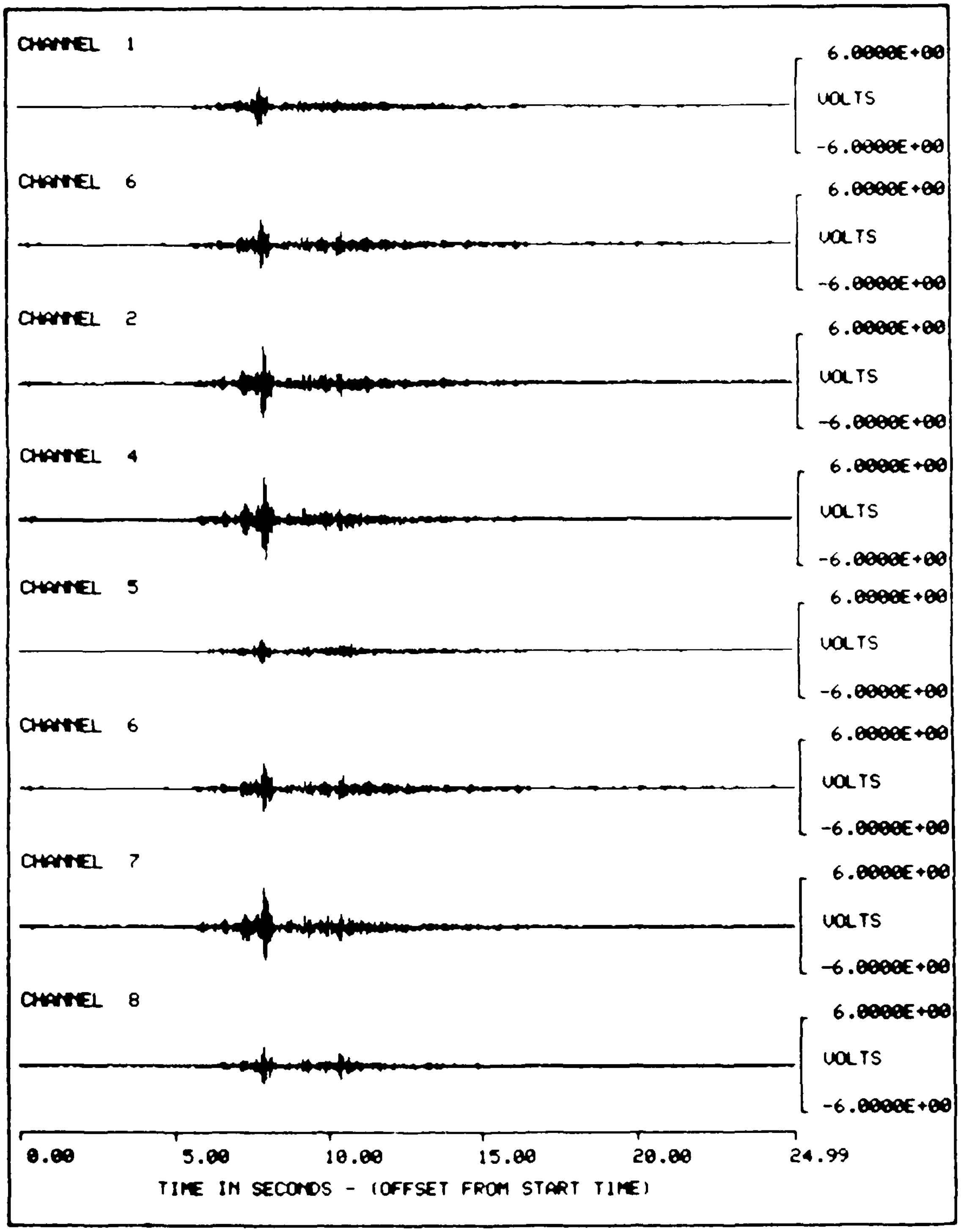
PRESSURE-EAST TRACK/CALM (RUN26)



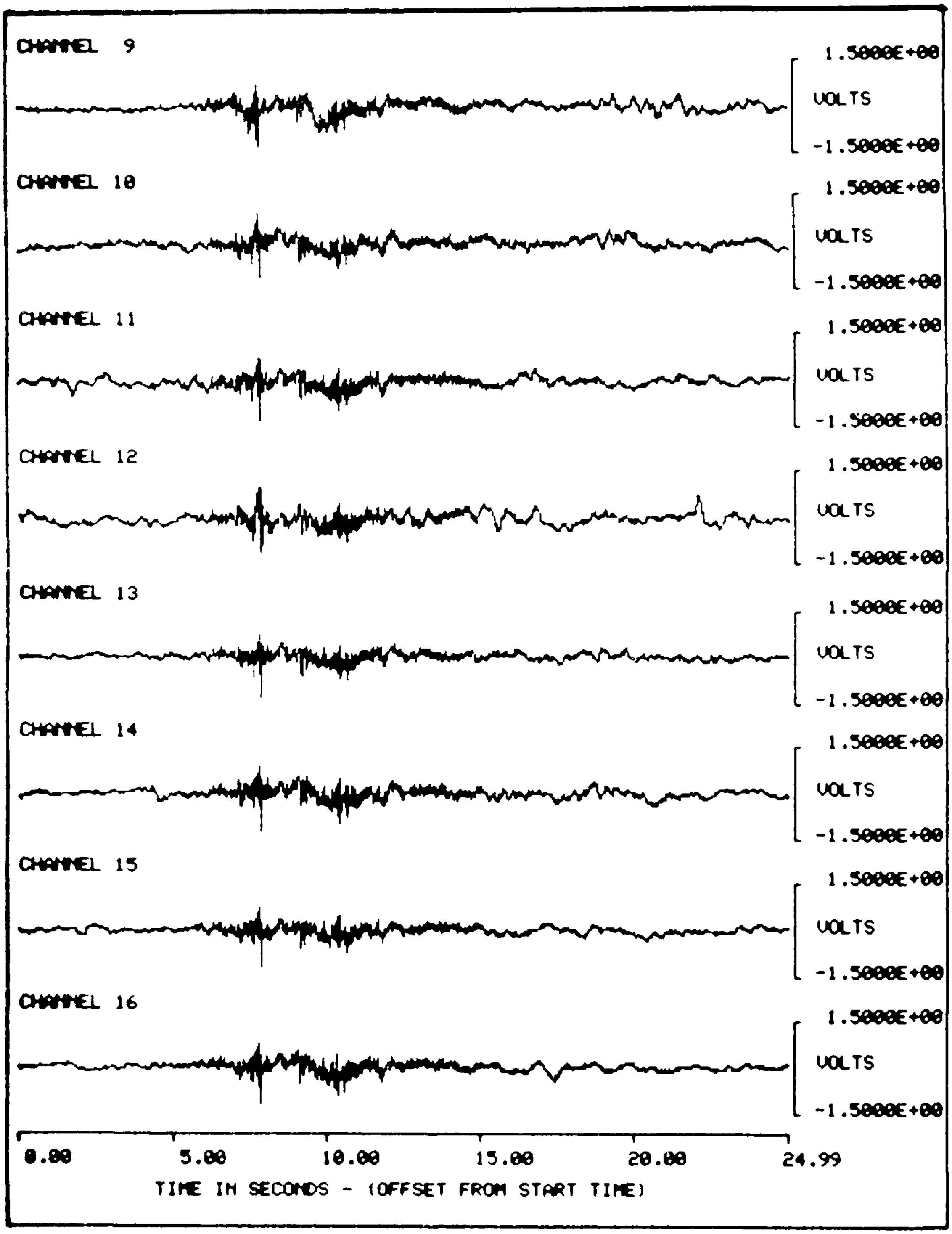
SEISMIC-EAST TRACK/WINDY (RUN 11)



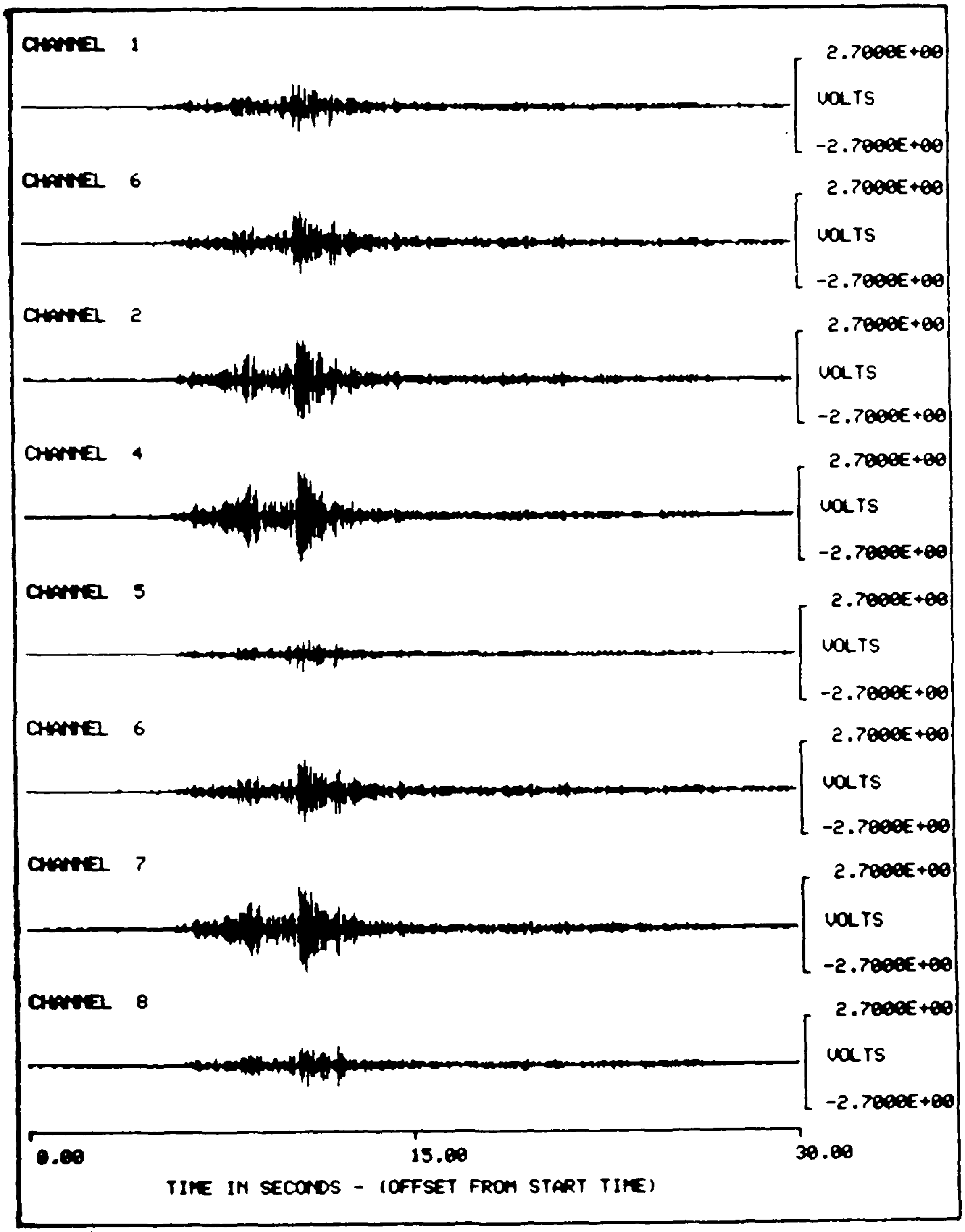
PRESSURE-EAST TRACK/WINDY (RUN11)



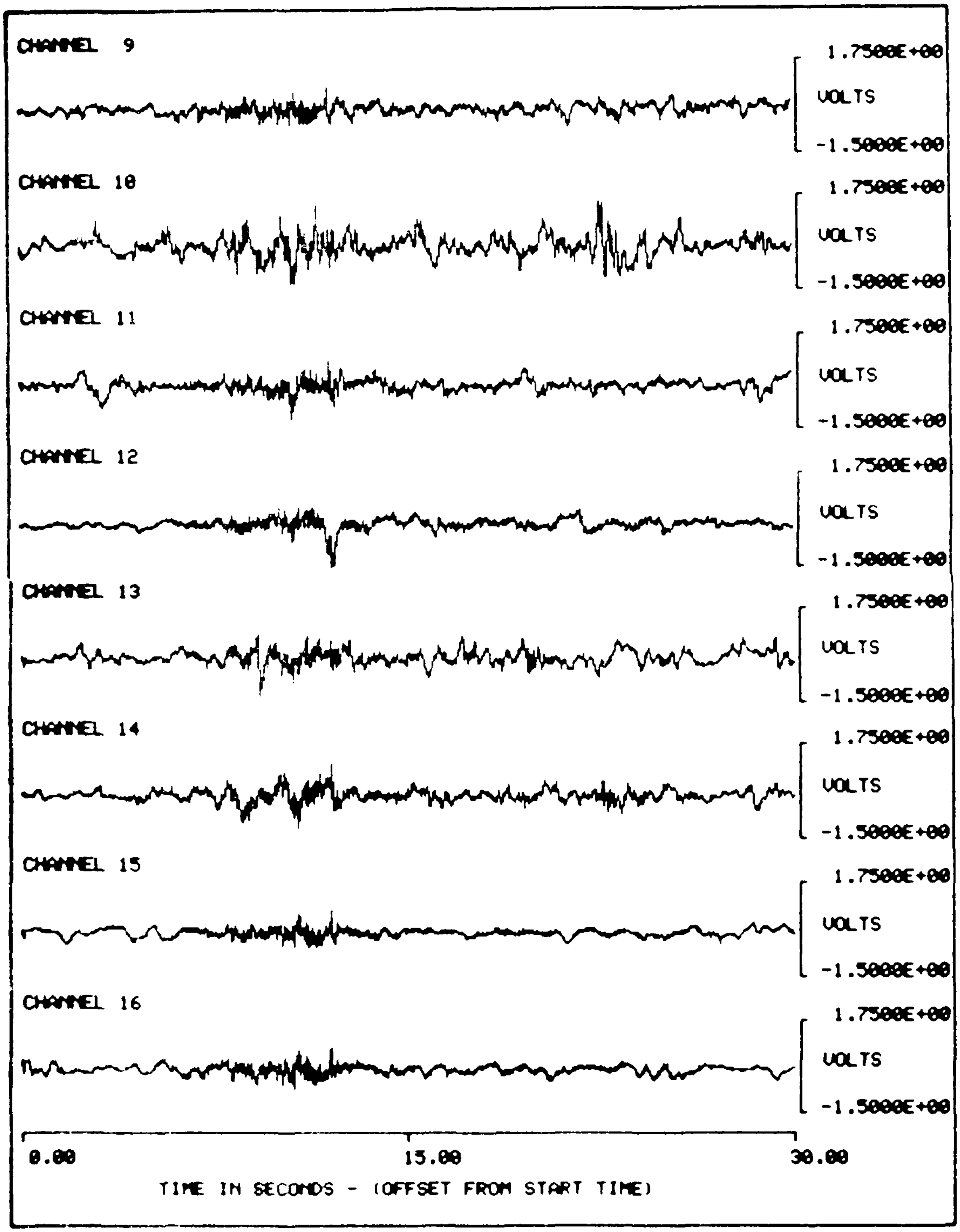
SEISMIC-WEST TRACK/CALM (RUN 08)



PRESSURE-WEST TRACK/CALM (RUN 08)



SEISMIC-WEST TRACK/WINDY (RUN 13)



PRESSURE-WEST TRACK/WINDY (RUN 13)

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